IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

In re Application		**PATENT APPLICATION**
Inventor(s):	Patrick P. Naulleau	
SC/Serial No.:	09/981,500	Art Unit: 2872
Confirm. No.:	6932	Examiner: Lavarias, Arnel C.
Filed:	October 16, 2001	
Title:	A HOLOGRAPHIC ILLUMINATOR FOR SYNCHROTRON-BASED PROJECTION LITHOGRAPHY SYSTEMS	**Customer No. 23910**

DECLARATION OF PATRICK P. NAULLEAU, Ph.D.

Commissioner for Patents
PO Box 1450
Alexandria, VA 22313-1450

Sir:

I, Patrick P. Naulleau, declare that:

1. I am the inventor of the above-identified patent application. I have been informed by counsel that the pending claims have been rejected in part based on Hamano, U.S. Patent Publication No. US2002/0001109 A1, published January 3, 2002 and filed May 30, 2001.

2. Prior May 30, 2001, I had conceived the subject matter of the invention as defined by the pending claims. Attached hereto is a copy of the disclosure and record of the invention which I prepared and submitted to Patent Department at Lawrence Berkeley National Laboratory.

3. Also prior to May 30, 2001, I had demonstrated the feasibility of the claimed invention. Attached hereto are four memoranda which I prepared prior to May 30, 2001 documenting some of my work which was done at the Lawrence Berkeley National Laboratory located in Berkeley, California.

4. The four memoranda are entitled:

   (1) Alternate illuminator for the SES using a holographic, diffusing M7;
   (2) Visible-light, proof-of-principle implementation of the generalized-fill holographic illuminator;
   (3) E-beam written EUV blazed gratings; and
   (4) Generalization of theEUV holographic-diffuser SES illuminator, Rev 1.

5. With respect to the use of blazed phase devices as the holographic diffuser, Lawrence Berkeley National Laboratory had demonstrated unique capabilities in fabricating such devices as described in third memorandum. Indeed, prior to May 30, 2001, the Lab had

fabricated the blazed phase devices for the EUV holographic diffuser. These devices exhibited high-efficiency characteristics.

6. I described the use of blazed devices for the EUV holographic diffuser in both paragraph 3 of the first memorandum ("Alternate illuminator ....") and paragraph 6 and the second to last paragraph of the fourth memorandum ("Generalization ....") In the second to last paragraph of the fourth memorandum, I noted that based on a combination of modeling of holographic diffusers in general and actual measurements of blazed phase grating we had fabricated, I expected an efficiency of ~10% from the holographic EUV diffuser.

7. I hereby declare that all statements made herein of my own knowledge are true and that all statements made on information and belief are believed to be true, and further that these statements were made with the knowledge that willful false statements and the like so made are punishable by fine or imprisonment, or both, under §1001 of Title 18 of the United States Code and that such willful false statements may jeopardize the validity of the application or any patent issuing thereon.

Date: 6/8/04

P. Naulleau

Patrick P. Naulleau

LBL File No. C/B-1661

Date Recieved

LAWRENCE BERKELEY LABORATORY [redacted]

Disclosure and Record of Invention

This invention was made in the course of or under prime contract No. DE-AC03-76SF00098 between the U.S. Department of Energy and the University of California. This Disclosure and Record of Invention is prepared for the Office of the Assistant General Counsel for Patents, U.S. Department of Energy.

Mail completed disclosure to LBL Patent Department, 90-1121

Telephone ext. 7058 if you have questions regarding this form.

Title of Invention: A synchrotron based illuminator for small-field EUV lithography studies using a holographic diffuser

Please list names of those who contributed to the inventive thought and to the final result of the invention. If a patent application is filed the Patent Department will make a legal determination of inventorship.

Contributor(s): Full Name	Title/Position	Employer	Division	Phone No.	Mail Stop
Patrick P. Naulleau	Optical Scientist	LBNL	MSD	4529	2-400

Contributor(s) Permanent Home Address(es):

Name	Citizenship	Street Address	City, State, and Zip Code
Patrick Naulleau	USA	5239 Miles Ave, Apt. A	Oakland, CA, 94618

IMPORTANT - Check the funding source for this invention & provide the information requested:

__ DOE only ; B & R Code ________ (See Division office for appropriate B & R code)
DOE Program Mgr.

__ Non DOE sponsor (including WFO)
Sponsor Name ________

__ CRADA
Private Sector Participant EUV/LLC

__ Subcontract
Subcontract No. ________ Contractor ________

__ Other
Describe ________

LBL Account Number 8336-12 LBL Principal Investigator David Attwood

From what source do you reasonably expect future or continuing funding?

Source EUV/LLC Is this ✓ continuing funding or __ future funding?

__ No future funding is currently expected.

Conception (Date, Place):

Earliest documentation of your invention: (please provide date and identify the document)

First Sketch or Drawing:

First Written Description: [redacted], part of transparency presentation at the EUV All Hands Meeting at LLNL

Names of witnesses or others with knowledge of facts relating to conception:

Jeff Bokor	Keith Jackson	Phil Batson

Reduction to Practice:

Date first model completed:

Date of operation and testing:

Place of test:

Results of testing:

Witnesses or others with direct knowledge of test:

Important: WAS ANY PROPRIETARY MATERIAL FROM OUTSIDE YOUR LABORATORY USED TO DEVELOP YOUR INVENTION (e.g., software code, cell line, antibody, DNA fragments, or chemical compound)? If yes, please describe.

NO

DESCRIPTION:

Background of the invention   Please summarize:

1) Technical problems overcome to make the invention,
2) What your invention enables people to do that couldn't be done as well before,
3) How people currently address the problem your invention addresses.

EUV Lithography is an emerging technology in the microelectronics industry. It is one of the leading candidates for the fabrication of devices with feature sizes of 70 nm and smaller. Synchrotron radiation facilities provide a convenient source of EUV radiation for the development of this technology. Currently the coherence and high flux properties of synchrotron undulator radiation is being used for crucial at-wavelength interferometry and alignment of complex EUV lithography optics. These interferometry results can be used to predict imaging performance, however, the final performance metric must always be actual imaging. It would be greatly beneficial to enable imaging studies to be performed at the same location as is performed the interferometry. The problem is, however, that relevant imaging studies require the use of partially coherent light as opposed to the coherent illumination required for interferometry and provided by the undulator beamline. The invention presented here allows the effective coherence of an undulator beamline to be tailored to small-field imaging requirements.

The use of an EUV diffuser has been proposed as the key element for destroying the beamline coherence. Such a device would be the EUV analog of conventional optical ground glass. The problem with this method, however, is that the EUV diffuser is extremely difficult to implement. It requires the fabrication of an engineered random relief substrate well controlled both laterally and in depth. Nearly atomic level accuracy is required in depth. The method presented here implements the EUV diffuser holographically. The diffusion characteristics are encoded into spatial modulations of a periodic spatial carrier. This alleviates the need to fabricate a well controlled multilevel substrate, reverting to the more conventional in-plane patterning situation. In addition to the holographic diffuser, the illuminator presented here employs a simple stationary low-cost spherical mirror.

Summary of the Invention   Please include a sketch of the invention if possible (you may attach extra pages):

The goal of a lithographic illuminator is essentially to illuminate the reticle to be imaged with a range of angles. The partial coherence of the illumination (σ) is the ratio of the illumination angular range to the numerical aperture of the imaging system. Additionally, each of the illumination angles must be comprised of light that is incoherent with the light at all other illumination angles. This condition is readily achieved by scattering a beam of coherent light with a moving diffuser. Scatter from the diffuser creates the requisite angles of illumination and motion of the diffuser guarantees the mutual incoherence of all these angles, assuming the observation (or exposure) time to be long relative to the speed of motion.

The major difficulty in fabricating an EUV diffuser for use in a non-critical-illumination system (a system in which the diffuser is not re-imaged to the reticle) lies in the control required of the scattering angle of the diffuser. Intrinsic roughness caused by the processing involved in creating the custom relief substrate, tends to increase the scattering angle significantly above the angle desired for typical EUV systems. Typical EUV systems have numerical apertures ranging from 0.1 to 0.3, assuming a conventional coherence factor of 0.7 and magnification of 4, the diffuser would ideally have a scattering numerical aperture of approximately 1 degree. Uncontrolled roughness in a diffuser will typically scatter light over an angle of 10 degrees, leading to a two-dimensional loss factor of about 100 due to area effects. An additional loss factor of approximately 10 or larger would also be expected due to loss of multilayer reflectivity. These losses would have a dramatic effect on the optical throughput of the system.

The potential high-angle scatter and multilayer reflectivity loss problems can be mitigated by using a holographic diffuser and achieving the diffusion through in-plane spatial modulation of a periodic carrier as opposed to surface profile control. In the simple case of an amplitude hologram, ideal silicon substrates could be used for the multilayer base, essentially eliminating the intrinsic roughness. Binary phase holograms could also be used improving the diffraction efficiency at the possible cost of higher intrinsic roughness. However, because the binary phase hologram would require fewer steps and a lower overall phase height as compared to a conventional EUV diffuser, the intrinsic roughness could likely be better controlled. Even further diffraction efficiency could be obtained through the use of blazed-phase gratings at the possible cost of further increased intrinsic roughness.

The use of a holographic diffuser instead of a conventional diffuser imposes two new difficulties, however. The first difficulty is the presence of the zero order which must be eliminated prior to illumination of the reticle and the second is the increased spatial resolution demands on the lithography. The spatial carrier in the holographic diffuser has the effect of increasing the resolution requirements by, at least, a factor of 4. Both these limitations can be overcome by implementing a demagnifying spatial-filtering system after the diffuser. The spatial filter would eliminate the zero-order component of the holgraphic diffuser and the demagnifying system would relax the patterning-resolution requirements.

The demagnifying system is comprised of a simple spherical mirror used to re-image the diffuser to the reticle. The spatial filtering is provided by a stop placed between the diffuser and the spherical mirror that selects only the holographic order. Order separation is achieved in the stop plane by properly choosing the spatial-carrier frequency in the holographic diffuser and having the incoming illumination beam focused to the stop plane.

Because the demagnifying system reduction ratio has an inverse effect on numerical aperture, the numerical aperture required of the holographic diffuser is, in fact, smaller than the illumination numerical aperture sought at the reticle. This has the effect of relaxing the holographic diffuser fabrication resolution requirements.

As with any illuminator relying on a diffuser to destroy the coherence of a coherent beam, the holographic diffuser must be moved at rate fast relative to the observation (exposure) time in order for the desired coherence modification to be achieved. Without motion, the diffuser creates the requisite multiple angles of illumination, however, the light at each of these illumination angles remains mutually coherent as they are all derived for a single coherent beam. Incoherence requires both multiple angles of incidence and mutual incoherence of all these angles. This effect can be effectively achieved by rapid motion of the diffuser. In the case of the holographic diffuser, however, the diffuser cannot simply be rotated as is typically done with conventional diffusers because this would cause the carrier to rotate in space. Instead, the holographic diffuser must be translated in *x* and *y* only.

Figure 1 shows the configuration for this illuminator. Refer to the attached "Alternate illuminator for the SES using a holographic, diffusing M7" memo for further implantation details.

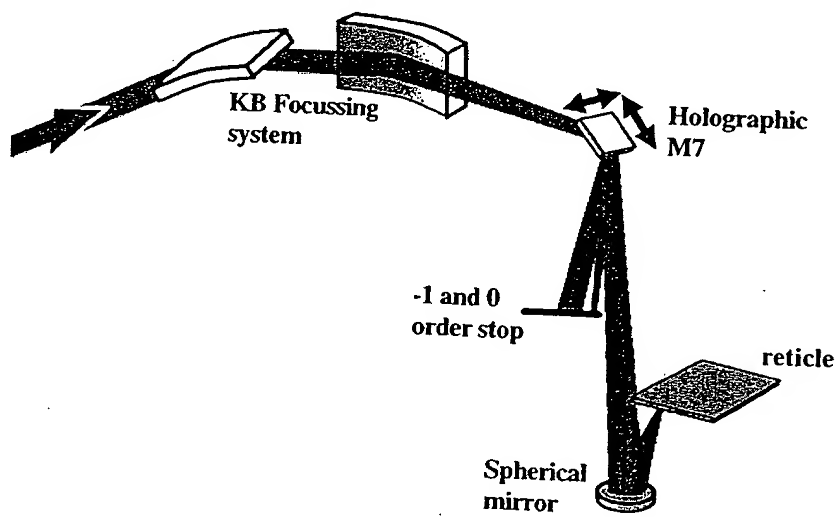

Fig. 1. EUV holographic diffuser illuminator design.

List uses of the invention - research, commercial, pilot plant, etc.; Think as broadly as possible. Identify companies that might be interested in licensing this technology.

Illumination systems for devices requiring incoherent illumination. EUV microscopy. EUV lithography. EUV coherence tomography.

Publications (including LBL reports, meeting abstracts, or prior patents or patent applications) that ACTUALLY DESCRIBE or RELATE to the invention:

Title/Subject	Publication Date	Indicate "Describes" or "Relates" to Inv.	Journal and/or LBL Rep. No. If prior LBL pat. appl., IB#
An alternate illuminator for the SES using a holographic, diffusing M7	[redacted]	Describes	CXRO internal memo

Papers you have SUBMITTED or are PREPARING for publication that describe or relate to your invention:

Title/Subject	Anticipated Publ. Date	Indicate "Describes" or "Relates" to Inv.	Journal and/or LBL Rep. No. If prior LBL pat. appl., IB#

Please notify the Patent Dept. (x7058) if you later plan new publications that describe or relate to the invention.

I believe myself to have contributed to be the above-described invention. (Each contributor must sign.)

CONTRIBUTOR: ____________________ DATE: ____________

WITNESS: ____________________ DATE: ____________

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WITNESS: ____________________ DATE: ____________

Read and Understood by:

____________________ Date: ____________

LBL Patent Department Reviewer

BERKELEY LAB

MATERIALS SCIENCES DIVISION

CENTER FOR X-RAY OPTICS

MEMO

To: Keith Jackson

From: Patrick Naulleau

CC: Phil Batson, Seno Rekawa, Ken Goldberg, and Jeff Bokor

Date: [redacted]

Re: Alternate illuminator for the SES using a holographic, diffusing M7

The success of the Subfield Exposure Station for static printing with ETS optics at the ALS as currently envisioned relies heavily on the development of an EUV diffuser[1,2] to be used as the crucial component of the illuminator. The diffuser approach has several advantages, including its simplicity and flexibility in terms of optical design, and its mechanical simplicity and small space requirements. The difficulties involved in the actual fabrication of the diffuser, however, make it a rather high-risk approach. To mitigate risk to the overall project, alternative "backup" illuminators have been designed. Here we describe one of these illuminators.

The major difficulty in fabricating the EUV diffuser for use in a non-critical-illumination system lies in the control required of the scattering angle of the diffuser. Intrinsic roughness caused by the processing involved in creating the custom relief substrate, increases the scattering angle significantly above the desired 1 to 2 degree half-angle scatter. This in turn has a dramatic effect on the optical throughput of the system.

The potential high-angle scatter problem can be mitigated by using a holographic diffuser and achieving the diffusion through in-plane spatial modulation of a periodic carrier as opposed to surface profile control. In the simple case of an amplitude hologram, ideal silicon substrates could be used for the multilayer base, essentially eliminating the intrinsic roughness. Binary phase holograms could also be used, improving the diffraction efficiency at the possible cost of higher intrinsic roughness. However, because the binary phase hologram would require fewer steps and a lower overall phase height as compared to the diffusers described earlier,[1,2] the intrinsic roughness could likely be better controlled. Even further diffraction efficiency could be obtained through the use of blazed-phase gratings.

The problem with the holographic diffuser is that elimination of the zero order and extremely high-resolution spatial patterning is required. The spatial carrier increases the resolution requirements by, at least, a factor of 4. These limitations can be overcome by implementing a demagnifying spatial-filtering system after the diffuser. The spatial filter would eliminate the zero-order component of the hologram and the demagnifying system would relax the patterning-resolution requirements.

The current design for the diffuser-based illuminator does not easily accommodate an additional imaging system between the diffuser and the reticle, therefore the diffuser would have to be located earlier in the optical path. A convenient location is on the M7 turning mirror currently used to redirect the undulator beam into the interferometer at the proper angle. As with the mechanical M7 illuminator design described elsewhere,[3] a spherical mirror can be positioned below the reticle stage to re-image M7 (which in this case incorporates the holographic diffuser) to the reticle. The spatial filtering of the zero order is achieved through free-space propagation, a stop, and a spatial carrier of adequately high

frequency in the hologram. Order separation at the stop can be further guaranteed by forcing the incoming beamline illumination to focus to the stop plane. In this case the zero-order of the holographic diffuser, which is essentially an unmodified version of the illumination beam, will be as small as possible in the stop plane.

It should be noted that unlike the non-critical diffuser-based illuminator, this system does not allow for *in situ* control of the coherence.

Figure 1 shows the configuration for the holographic illuminator described here. The imaging mirror is placed in the same position as would be the conventional diffuser (100 mm below is the object plane). The holographic diffuser is incorporated into the M7 mirror positioned approximately 237 mm above the object plane. This configuration yields a reduction ratio of 3.34 from the holographic diffuser to the reticle.

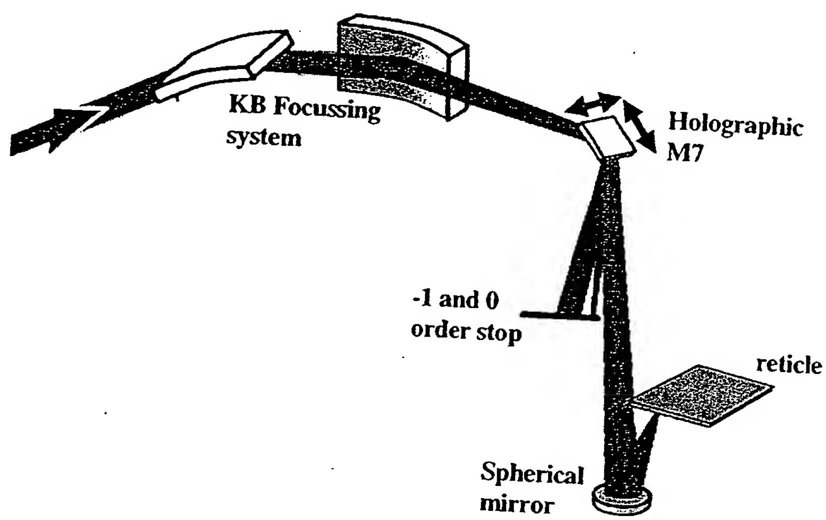

Fig. 1. Schematic of the holographic diffusing M7 critical illuminator alternative for the SES.

Because the reduction ratio has an inverse effect on numerical aperture (NA), the NA required of the holographic diffuser is 3.34 times smaller than the illumination NA sought at the reticle. To achieve a σ of 0.7 with the ETS optic (object-side NA = 0.025), the required holographic diffuser NA is $(0.7)(0.025)/3.34 = 0.0052$. This condition significantly relaxes the holographic diffuser fabrication requirements. Figure 2 shows the one-dimensional, single-sided spectrum of the holographic diffuser in the direction of the carrier. The carrier frequency (θ_c) should be chosen such that separation is achieved between the diffracted order and the zero order. Noting that the zero order is in general twice as wide as the diffracted order, the carrier frequency should be at least 1.5 times larger than the NA desired from the holographic diffuser. Additionally, in order to facilitate the selection of the diffracted order by way

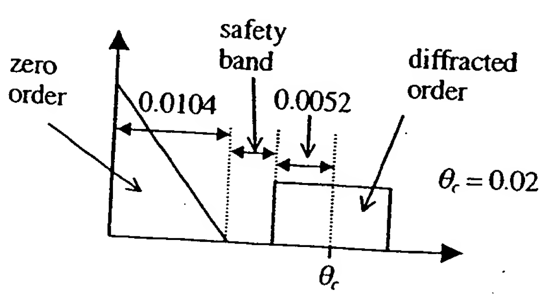

Fig. 2. Single-sided, one-dimensional spatial frequency spectrum of a typical holographic diffuser in the direction of the carrier.

of a spatial filter, an extra safety band should be added (Fig. 2). Choosing a safety band approximately equal to the desired NA sets the carrier frequency (angle) to 0.02 rad (1.15°). This corresponds to a holographic carrier period of 670 nm. To achieve the desired NA from the diffuser requires the carrier to be modulated at a resolution of approximately 250 nm. These specifications are well within the capabilities of current lithography tools including the CXRO *Nanowriter*.

It is also important that the imaging mirror itself not limit the illumination NA. Given the position of the imaging mirror, its diameter is simply required to be larger than 5 mm to satisfy this condition. Because the spherical imaging mirror is a condenser mirror, the wavefront specifications can be rather loose. The required specifications for this case are identical to those described for the scanning-angle M7 illuminator.[3]

As with any illuminator relying on a diffuser to destroy the coherence of a normally coherent beam, the holographic diffuser must be moved at rate fast relative to the observation (exposure) time in order for the desired coherence modification to be achieved. Without motion, the diffuser creates the requisite multiple angles of illumination, however, the light at each of these illumination angles remains mutually coherent as they are all derived for a single coherent beam. Incoherence requires both multiple angles of incidence and mutual incoherence of all these angles. This effect can be effectively achieved by rapid motion of the diffuser. In the case of the holographic diffuser, however, the diffuser cannot simply be rotated as this would cause the carrier to rotate in space. Instead, the diffuser must be translated in x and y only.

As with the scanning-angle M7 illuminator,[3] the system described here is a critical illuminator. Care must be taken to avoid non-uniformities at the diffuser from being transferred to the illumination of the reticle.

We note that we have previously rejected the idea of using naturally rough diffusers for the non-critical illuminator[2] due to the uncontrollably large scatter angle greatly reducing the optical throughput of the system. This is caused by illuminating a much larger portion of the reticle than is in fact desired in addition to the induced multilayer reflectivity loss. In principle, a critical system like the one described here could be used to mitigate this problem. The obvious choice would be to replace the M7 mirror with a naturally rough diffuser. Such a diffuser, however, would have a scatter half angle of approximately 10° and would require a 116-mm diameter condenser lens to achieve the desired throughput gains in the SES configuration. Such a large diameter condenser would not be mechanically compatible with the current system, and furthermore the additional NA would not be accepted by the ETS optic thereby negating the collection gain of the condenser. Also, the roughness induced multiliayer reflectivity loss is not addressed by the condenser solution. The method could be feasible, however, assuming a complete redesign of the illumination-system light path and that the roughness-induced multilayer loss is tolerable.

References

1. P. Naulleau, "Modeling of EUV diffusers compatible with electron-beam lithography fabrication methods," [redacted]
2. P. Naulleau, "EUV diffusers for synchrotron-based imaging experiments," [redacted]
3. P. Naulleau, "An alternate illuminator for the SES," [redacted]

MEMO

Materials Sciences Division
Center for X-Ray Optics

To: Keith Jackson
From: Patrick Naulleau and Erik Anderson
CC:
Date: [redacted]
Re: Visible-light, proof-of-principle implementation of the generalized-fill holographic illuminator

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The development of the Subfield Exposure Station (SES) for static printing with ETS optics at the EUV interferometry beamline has led to the design of various decoherentizing small-field illuminators including a holographic illuminator capable of producing a generalized fill pattern.[1-2] This illuminator uses a holographic optical element (HOE) to serve as the new effective illumination source.

In general, an HOE can be designed to generate any arbitrary far-field diffraction pattern. When such an element is used as the source in a critical illumination system (Fig. 1), any arbitrary pupil-fill pattern can be synthesized. In this case, the reticle-plane illumination pattern is set by the HOE-plane illumination pattern.

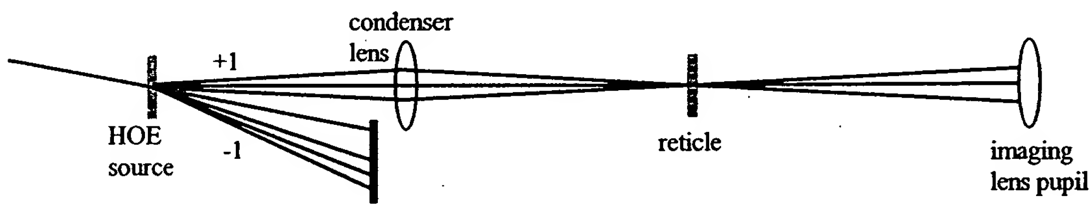


Fig. 1. Critical illuminator using an HOE-synthesized source.

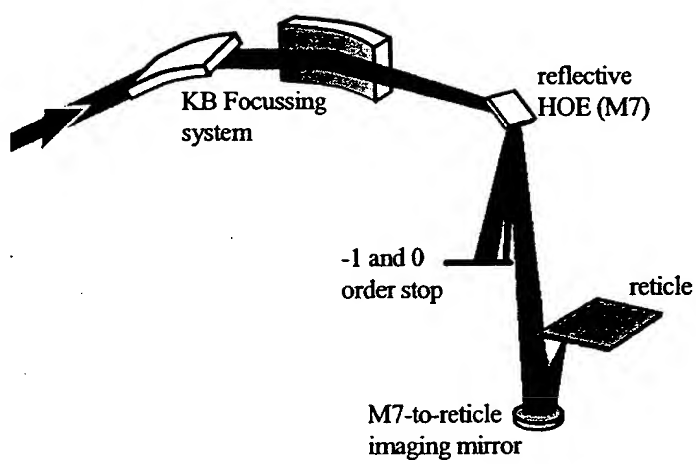


Fig. 2. SES implementation of HOE-synthesized source critical illuminator.

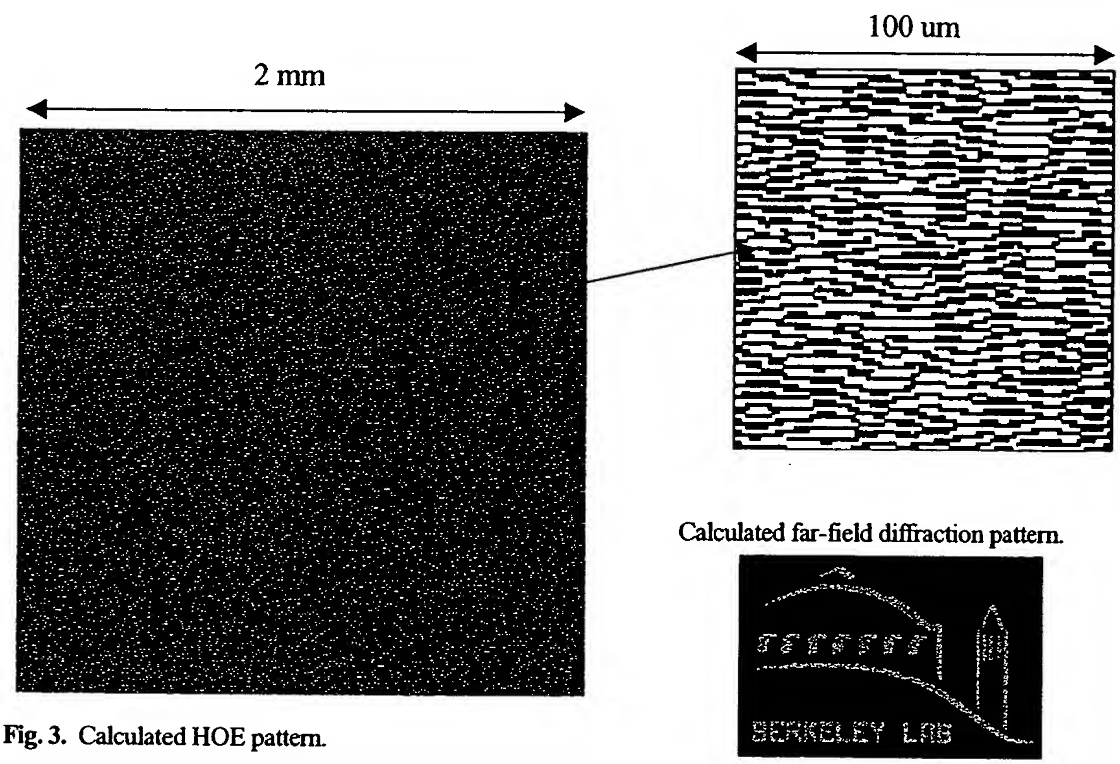
The HOE could be a transmission device as depicted in Fig. 1, or a reflection device. The reflection implementation is attractive for EUV applications because it allows the HOE to be integrated into an existing optical component, thus, simplifying the system design and optimizing throughput. Figure 2 shows such an implementation for the SES (this configuration is described in detail in Refs. 1 and 2).

As described previously,[2] the EUV implementation of the HOE is ideally a phase-only device and is, furthermore, preferably realized using a binary-phase carrier. The HOE pattern required to

generate any arbitrary fill pattern under this restrictive condition can be computed by way of iterative phase-retrieval techniques.[2-4]

The feasibility of implementing such a device at EUV has been demonstrated by fabricating a visible-light analog. The off-axis, pure-phase HOE has been designed to generate the LBL logo using the iterative phase-retrieval method. The binary-phase carrier is created by producing a two-level relief pattern onto a silicon wafer. The device is rendered uniformly reflective at visible light by aluminum plating. To create an EUV device, the aluminum coating would simply be replaced by an appropriate reflective multilayer coating. The lithographic patterning was done using the CXRO *Nanowriter* electron-beam lithography tool.

Figure 3 shows the calculated HOE pattern used as the basis for the *Nanowriter* patterning along with the corresponding calculated far-field diffraction pattern.. The HOE pattern is 2048×2048 pixels and covers at total area of 4 mm^2. The HOE is designed to work at a wavelength of 633 nm and 20 degrees off normal. Accordingly, the binary pattern height is 168 nm. The black regions correspond to locations that are 168 nm taller than the white portions.



Calculated far-field diffraction pattern.

Fig. 3. Calculated HOE pattern.

Figure 4 shows the actual fabricated HOE wafer; 5 identical HOEs have been patterned near the center of the wafer. Also shown are two orders (the desired pattern and its complex conjugate) of the HOE diffraction pattern under He-Ne illumination.

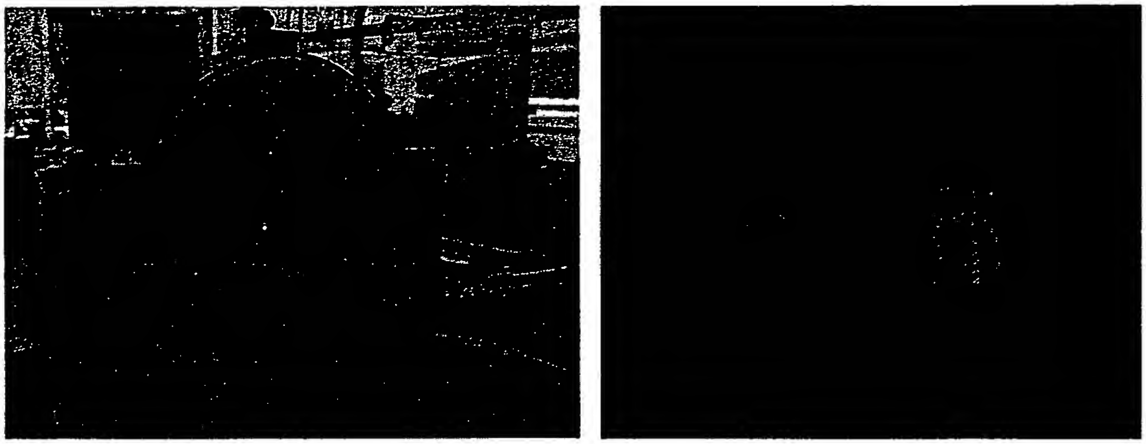


Fig. 4. Fabricated visible-light phase only off-axis HOE with binary phase carrier and its measured diffraction pattern.

This visible-light implementation demonstrates that using relatively simple binary height fabrication methods, we have the ability to produce HOEs with arbitrary diffraction patterns. Applying this to EUV would provide the basis for an arbitrary-fill illuminator. Completely redefining the fill would simply require changing one flat reflective optical element. We note that the *Nanowriter* used in this demonstration has ample resolution for the EUV implementation as well.

References

1. P. Naulleau, "Alternate illuminator for the SES using a holographic, diffusing M7," [redacted]
2. P. Naulleau, "Generalization of the EUV holographic-diffuser SES illuminator, Rev 1," [redacted]
3. R. Gerchberg and W. Saxon, "A practical algorithm for the determination of phase from image and diffraction plane pictures," Optik, **35**, 237-246 (1972).
4. J. Fienup, "Reconstruction of an object from the modulus of its Fourier transform," Opt. Lett., **3**, 27-29 (1978).

MEMO

BERKELEY LAB

MATERIALS SCIENCES DIVISION

CENTER FOR X-RAY OPTICS

To: Dan Tichenor

From: Patrick Naulleau and Erik Anderson

CC: David Attwood, Jeff Bokor, Ken Goldberg, Keith Jackson, Rick Stulen

Date: [redacted]

Re: E-beam written EUV blazed gratings

The use of a single-exposure method for fabricating the reflective EUV diffuser to be used in the static imaging Sub-field Exposure Station (SES) has shown great promise. This method uses a grayscale e-beam exposure to produce continuous-height relief structures directly in resist. The relief structure is then overcoated with a conventional Mo/Si multilayer. Thus far, the best performing resist, in terms of intrinsic roughness, has been found to be HSQ (a glass-based resist).

As part of the process-development procedure for the diffuser-fabrication task, we have produced a variety of reflective EUV blazed gratings. Such gratings could also serve as the basis of a recently proposed spectral purity filter for the ETS, where a grating monochromator replaces the transmission membrane filter. Here, we summarize the current performance of the e-beam-fabricated blazed gratings.

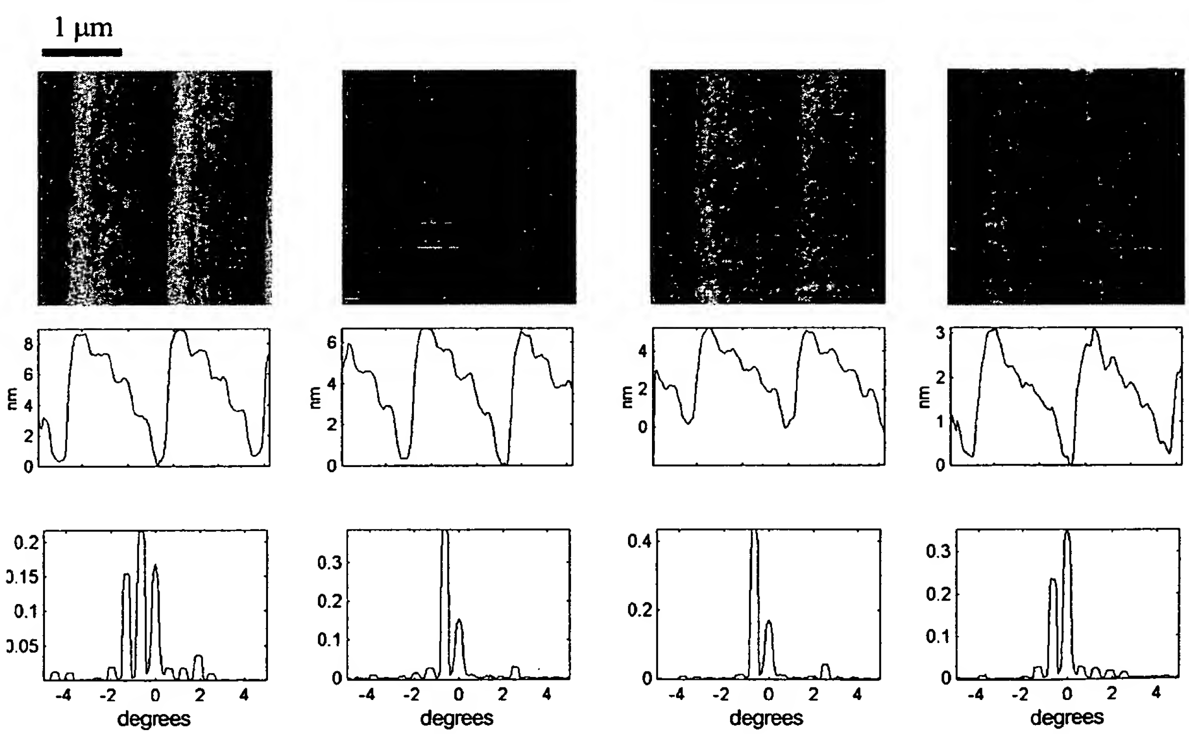


Fig. 1. AFM images and average profiles for four sample gratings relatively close to the ideal modulation height for the +1 order blaze condition along with diffraction plots obtained using the Beamline 6.3 reflectometer. The undisturbed multilayer reflectivity has been normalized out of the diffraction plots.

The first two rows in Fig. 1 show AFM images and average profiles for four sample gratings with heights relatively close to the ideal modulation height for the +1-order-blaze condition. The third row shows reflectometry results obtained at Beamline 6.3, demonstrating the diffraction efficiency of each grating. The undisturbed multilayer reflectivity has been normalized out of the diffraction plots.

As demonstrated in Fig. 1, a diffraction efficiency exceeding 40% has been obtained. Noting that this result comes from a simple 5-level grating with non-optimized step sizes, exceeding diffraction efficiencies of 50% seems well within range. Also possibly limiting the diffraction efficiency measured here is intrinsic roughness in the resist. This effect might be reduced through the use of Ion Beam sputtering as opposed to the Magnetron sputtering used for the multilayers studied here. Ion Beam sputtering would increase the smoothing characteristics of the multilayer. Other methods such as annealing of the resist prior to multilayer deposition may also reduce the intrinsic roughness, thus increasing the efficiency of the gratings.

BERKELEY LAB
MATERIALS SCIENCES DIVISION
CENTER FOR X-RAY OPTICS

MEMO

To: Keith Jackson
From: Patrick Naulleau
CC: Erik Anderson, Ken Goldberg, and Jeff Bokor
Date: [redacted]
Re: Generalization of the EUV holographic-diffuser SES illuminator, Rev 1

The development of the Subfield Exposure Station (SES) for static printing with ETS optics at the EUV interferometry beamline has led to the design of various decoherentizing small-field illuminators.[1-4] These illuminators all provide conventional fill patterns whereas the ETS illuminator utilizes a discretized fill pattern. As designed, the SES will, thus, not be able to characterize ETS-illuminator effects on the imaging performance. This limitation could be overcome through the implementation of a generalized version of the previously described holographic diffuser illuminator.[4]

The previously described holographic diffuser[4] can be viewed as a special case of a holographic optical element (HOE). In general, an HOE can be designed to generate any arbitrary far-field diffraction pattern. When such an element is used as the source in a critical illumination system (Fig. 1), any arbitrary pupil-fill pattern can be synthesized. In this case, the reticle-plane illumination pattern is set by the HOE-plane illumination pattern. Using an HOE-based illuminator would, thus, allow the actual ETS fill pattern to be simulated in the SES as well as enabling the experimental investigation of any other arbitrary fill pattern.

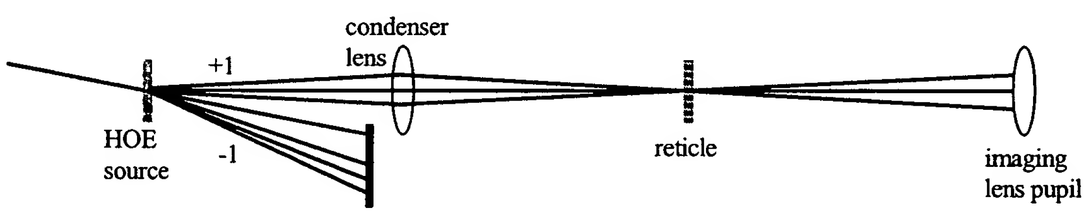


Fig. 1. Critical illuminator using an HOE-synthesized source.

It is also interesting to note that when the HOE is used as the source in a Köhler illuminator, the HOE designed diffraction pattern becomes the reticle-plane illumination and the pupil fill is set by the HOE-plane illumination pattern.

Given a desired far-field diffraction pattern, the corresponding HOE can be calculated as one would calculate the Fourier-transform hologram of the diffraction pattern. This is done by calculating the Fourier transform of the desired pattern and modulating a spatial carrier using the resulting complex-valued Fourier transform. The ideal HOE will have a sinusoidal carrier and will include both amplitude (contrast) and phase modulation of the carrier.

In the visible-light regime, an ideal HOE could be readily recorded by recording a Fourier-transform hologram of the desired diffraction pattern generated by some other means. The transmission device

could then be used as the synthesized source in Fig. 1. At EUV wavelengths, however, the process is not so convenient due to lack of equivalent holographic film. We are, in practice, typically limited to calculating the HOE as described above and using lithographic techniques to generate the pattern or a reasonable approximation of the pattern.

The final HOE could be a transmission device fabricated using the same techniques used when fabricating gratings for EUV interferometry. The gratings can be either amplitude or Molybdenum phase gratings.[5] The advantage to using Molybdenum phase gratings is increased efficiency. Alternatively, the HOE could be fabricated as a reflection device using methods similar to those used to generate high-efficiency reflection EUV blazed-phase gratings.[6]

The reflection method is attractive for the SES because it allows the HOE to be integrated into an existing optical component (the M7 turning mirror), thus, simplifying the system design. A diagram of the SES with such an illuminator is shown in Fig. 2. This configuration is identical to that shown in Ref. 4 which, as stated above, describes a special case of the HOE illuminator presented here.

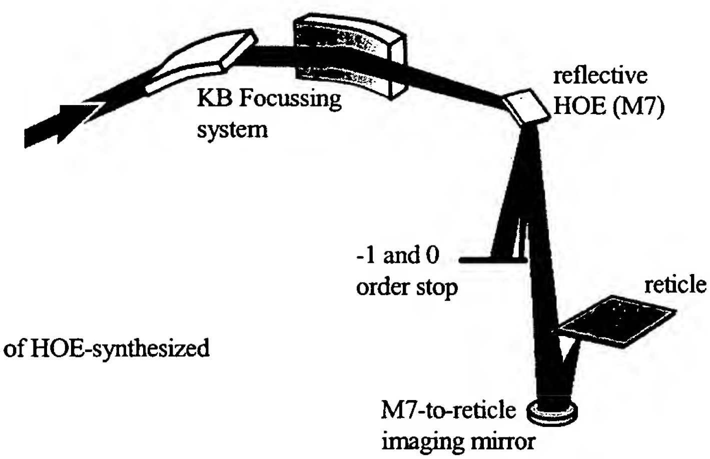


Fig. 2. SES implementation of HOE-synthesized source critical illuminator.

When lithographically fabricating a computer-generated HOE it is difficult to pattern the ideal modulated sinusoidal carrier. In practice, we are typically restricted to binary patterns making amplitude modulation of the carrier impossible. We note that amplitude modulation can be effectively achieved through duty-cycle modulation, however, it is often adequate to employ phase-only modulation, facilitating the fabrication process. Furthermore, in the critical configuration is it preferable to have phase-only modulation because any amplitude modulation would become illumination non-uniformity at the reticle plane.

When calculating the modulating function for a phase-only HOE intended to produce a specific diffraction pattern, two parameters are known: 1) the magnitude of the Fourier transform of the modulating function (the desired diffraction pattern) and 2) the amplitude of the modulating function (unity because it is a phase-only device). The problem is, thus, to determine the phase of the HOE (object) given the amplitude of its Fourier transform. This problem is similar to the astronomical problem of reconstructing an object given the magnitude of the Fourier transform of the object. To address this problem, several so-called phase retrieval algorithms have been developed based on iterative techniques.[7,8] These techniques can be readily applied to the phase-only HOE problem of interest here.

The simplest implementation of the iterative technique (the error-reduction method) works as follows:

1) Generate the desired magnitude diffraction pattern, $D'(f_x,f_y)$
2) Generate the seed diffraction pattern for calculation process, $D(f_x,f_y)$ (most conveniently unity)
3) Enforce constraints on $D(f_x,f_y)$ [multiply by the desired magnitude diffraction pattern, $D'(f_x,f_y)$]
4) Inverse Fourier transform $D(f_x,f_y)$ obtaining guess at the modulating signal, $d(x,y)$
5) Enforce constraints on $d(x,y)$ (force the amplitude to be unity)
6) Fourier transform $d(x,y)$ to generate resulting diffraction pattern, $D(f_x,f_y)$
7) Repeat steps 3 through 6 until the magnitude of the result of step 6 matches the desired magnitude diffraction pattern.

The iterative method described above has been used to calculate a phase-only HOE modulating function to generate an approximation to the ETS fill pattern. Figure 3 shows the resulting HOE modulating function diffraction pattern for various iteration numbers.

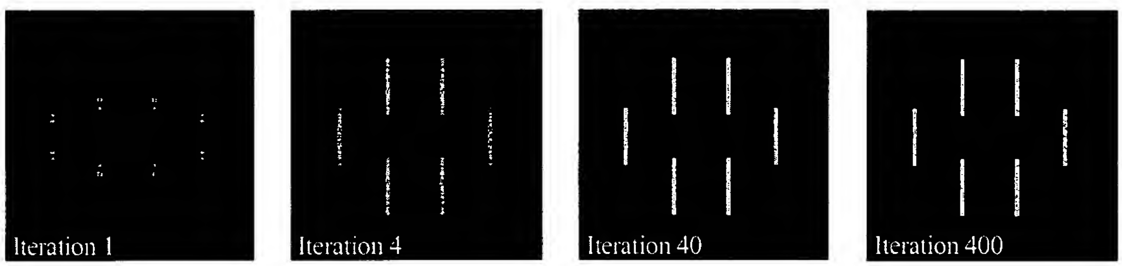


Fig. 3. Phase-only HOE modulating function diffraction pattern for various iteration numbers. The HOE has been designed to approximate the ETS fill pattern.

This modulating function must then be placed onto a spatial carrier to generate the actual HOE. As stated above, at EUV we are typically limited to binary carriers, either amplitude or phase. Figure 4 shows the resulting binary-phase carrier HOE as well as the diffraction pattern. The diffraction pattern contains both the desired pattern and its complex conjugate, the zero-order term is suppressed due to the phase-only carrier. The speckle seen in the actual HOE diffraction pattern is a result of the binary, resolution-limited carrier.

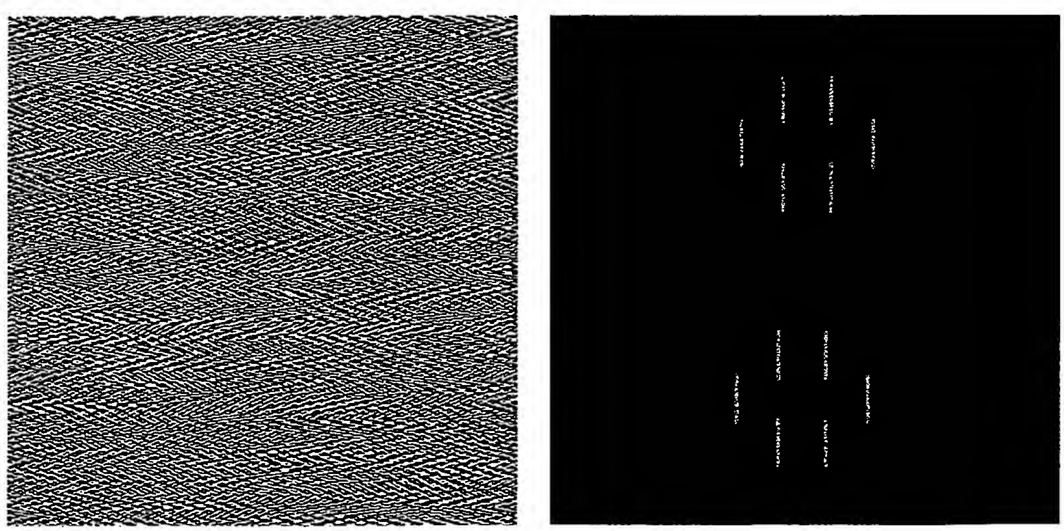


Fig. 4. Actual HOE pattern and far-field diffraction from HOE. The diffraction pattern contains both the desired pattern and its complex conjugate, the zero-order term is suppressed due to the phase-only carrier.

The method described above can be applied to any arbitrary fill pattern. Figure 5 shows the HOE diffraction patterns from HOEs designed for tophat, annular, quadrapole, and an arbitrary pattern comprised of the VNL and EUVL logos. The speckle is again a result of the binary, resolution-limited carrier. As described below, this speckle will be averaged away by the requisite motion of the HOE.

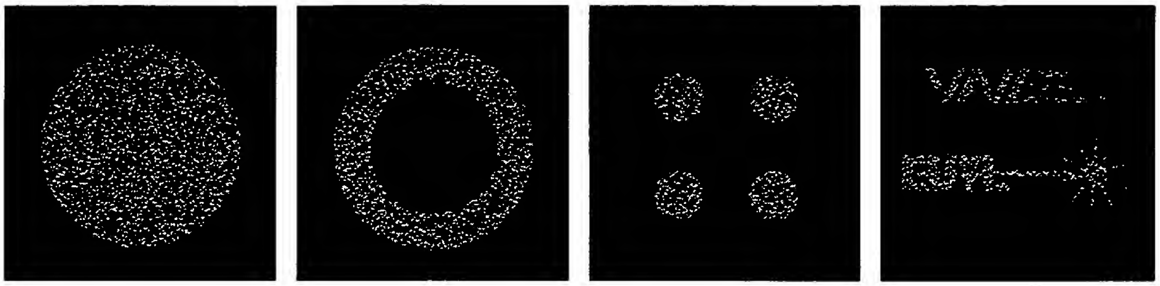


Fig. 5. Diffraction patterns from phase-only HOEs using binary phase-only carrier. The HOEs were designed to generate a variety of common fill patterns as well as an arbitrary fill pattern.

It is important to note that illumination partial coherence requires the individual spatial-frequency (angular) components to be mutually incoherent. The pupil plane images shown in Figs. 4 and 5 represent the angular spectrum of the reticle-plane illumination. To have partial coherence we, thus, require each point in the pupil map (far-field diffraction pattern) to be incoherent with all other points. Clearly this condition would not be achieved by simply illuminating the stationary HOE with a coherent beam.

The partial-coherence condition can, however, be met by generating a HOE that is larger than the illumination area of interest and moving the HOE relative to the illuminating beam during the exposure. This also requires the phase of the diffraction pattern generated by the HOE to have a negligible correlation length relative to the pupil diameter. The random phase condition is readily met by seeding the iterative HOE calculation process described above with a random phase term instead of using the unity seed described above.

As mentioned above, the HOE must be moved relative to the illumination beam during an exposure. Coherence control requires the HOE to be moved through approximately, at least, 1000 correlation lengths of the HOE. However, the illumination uniformity is approximately 1/sqrt(N) where N is the number of correlation cycles integrated over. For example, if only a single correlation cycle is sampled, the illumination pattern will be a fully developed speckle pattern. The contrast of the speckle pattern (or the illumination uniformity) will go as 1/sqrt(N). A 1% uniformity would thus require about 10000 correlation lengths to be covered. The speckle contrast in the pupil-fill pattern will also decrease at the same rate.

The correlation length of the HOE is readily determined from the bandwidth of the HOE carrier-centered signal. For the ETS 6-channel illuminator, this bandwidth is effectively the object-side numerical aperture of the POB (NA = 0.025) times the effective illuminator partial coherence (sigma = 0.7). This yields a single-sided angular bandwidth of 0.0175 and a correlation length on the order of 0.5 μm. Assuming two-dimensional motion of the HOE, moving through 10000 correlation lengths requires the HOE to be only approximately 50 μm larger than the desired illumination size in each direction. Thus, the required motion of the HOE does not significantly affect the required HOE size nor is it very demanding from the mechanical motion point of view.

The coherence-control characteristics described above have been verified by way of physical-optics modeling of the HOE illuminator. We begin by generating an HOE that is 60×60 μm large that generates a fill pattern matching that of the ETS. The pixel size in the HOE is 29 nm. We note that the pixel size was determined primarily based on numerical simulation considerations rather than physical patterning resolution requirements. Although the CXRO *Nanowriter* can readily achieve this resolution, a 4-times lower patterning resolution (~100 nm) would be adequate under the unity magnification condition between the HOE and the reticle. Even lower patterning resolution could be used in the case where a demagnifying system is used to re-image the HOE to the reticle, as described in Ref. 4.

The physical-optics simulation considered here assumes a unity magnification system to be used as part of the spatial filter that re-images the HOE to the reticle. A 15×15 μm illumination area is considered at the reticle (by definition the same illumination size is considered on the HOE). Both the coherence function and the illumination uniformity are determined at the reticle.

The simulation works by considering a coherently illuminated 15×15 μm area on the HOE and calculating the coherent reticle-plane distribution. The 60 μm HOE is then displaced relative to the 15 μm illumination area by ~0.25 μm and a new realization of the coherent reticle-plane distribution is calculated. This process is repeated until the entire 60 μm HOE area is covered. The independent realizations are summed in power to derive the time-integrated illumination uniformity.

The coherence function is determined by simulating the recording of a time-integrated hologram of the illumination where the center of the illumination pattern placed onto a spatial carrier is used as the reference beam. This models the well-established holographic method for measuring spatial coherence.[9] Reconstruction of the resulting time-integrated Fourier-transform hologram of the reticle-plane illumination yields the coherence function.

Figure 6 shows the 60 μm HOE along with a blow-up of a 6 μm area. Figure 7 shows the HOE diffraction pattern, more closely matching the design ETS fill pattern than the example shown in Figs. 3 and 4. Figure 8 shows the coherence function over a 15-μm region at the reticle. As one would expect due to the discretized fill, the coherence function is periodic in the direction where the fill is discrete. The coherence periodicity is seen to be 1.13 μm. Based on a channel separation in the pupil of 0.47 times the object-side numerical aperture of 0.025, the object-plane coherence periodicity can be calculated to be 1.15 μm, closely matching the simulated value. The coherence diameter at the reticle

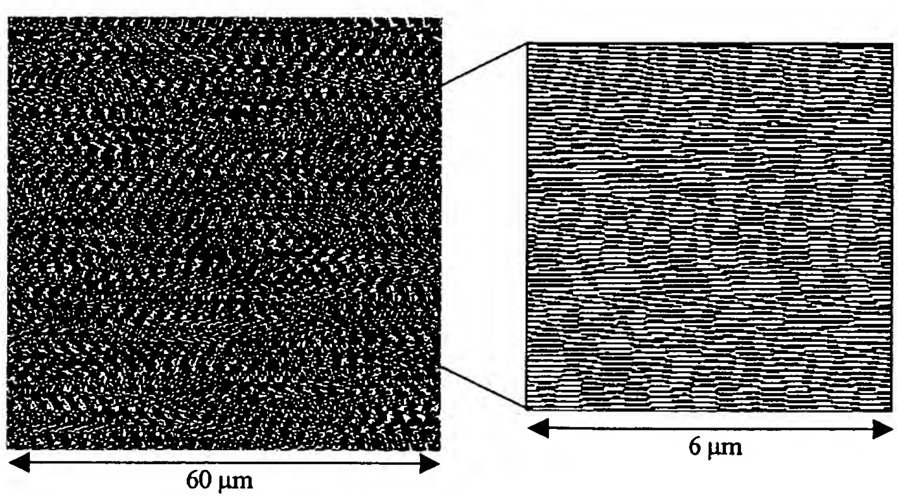


Fig. 6. 60-μm HOE designed to match ETS fill pattern along with blow-up of 6-μm central region.

plane is approximately 0.5 μm, slightly larger than the diffraction-limited resolution, as expected based on the desired sigma of 0.7. The time-integrated illumination uniformity as simulated in the reticle plane was found to be on the order of 0.5% peak-to-valley.

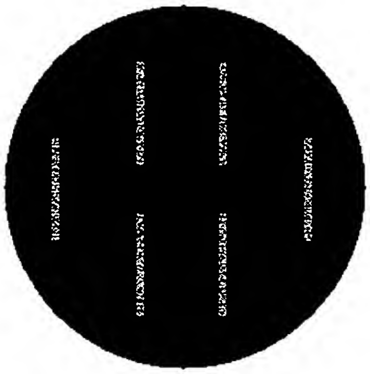


Fig. 7. Pupil fill generated by HOE depicted in Fig. 6. Full pictured object-side numerical aperture is 0.025.

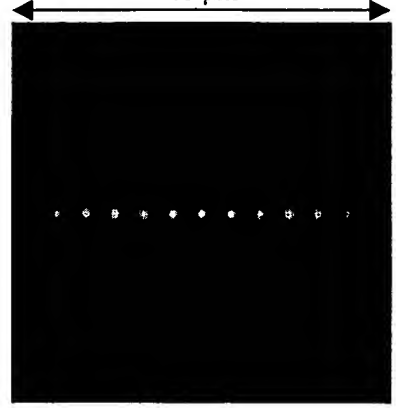


Fig. 8. Coherence function as simulated in the object plane. Coherence function is determined from simulated time-integrated hologram of the illumination generated by the moving HOE. The coherence periodicity expected based on the discretized pupil fill is evident.

In summary, a customizable fill synchrotron-based illuminator using a HOE has been presented. This illuminator has potentially much higher efficiency than the diffuser-based illuminator currently under development for the SES.[1,2] This is especially true as the numerical aperture increases; with the simple diffuser-based illuminator, it is not always possible to independently control both the illumination size and the coherence. The critical configuration of the HOE illuminator overcomes this problem. Also, the shorter substrate height modulation required for the HOE compared to the diffuser make intrinsic roughness of the engineered substrate less of an issue.[6] Based on recently fabricated EUV reflection blazed-phase gratings, an efficiency of ~10% could be expected from the HOE using current fabrication methods.[6]

The HOE illuminator is particularly interesting in that it allows arbitrary pupil-fill patterns to be tested with minimal reconfiguration of the system. Indeed, only the HOE itself need be replaced. Also, because of the critical configuration it is possible to simultaneously study a variety of fill patterns by making a HOE comprised of a variety of sub-HOEs each providing a different fill pattern to a different area on the reticle. For nominally 0.7 sigma fill patterns, the dead-band between the individual fill fields on the reticle caused by the required HOE motion would be only about 50 μm.

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